NEW SCENARIOS OF MICROBUNCHING INSTABILITY CONTROL IN ELECTRON LINACS AND FREE ELECTRON LASERS

Elettra Sincrotrone Trieste

Eléonore Roussel*

Elettra-Sincrotrone Trieste, Italy

∗ *present address: SOLEIL Synchrotron, France*

IPAC 2017 MAY 14 – 19

Outline

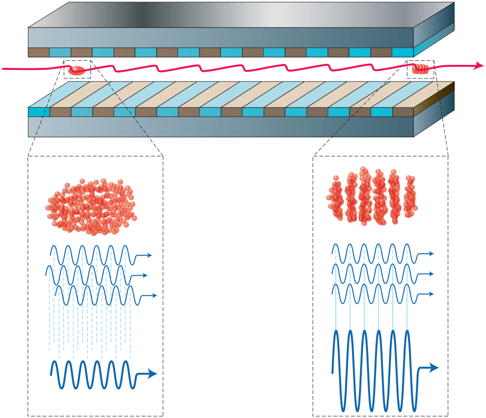
1. Introduction to the microbunching instability
2. Multicolor FEL driven by seeded microbunching instability
3. Towards tunable narrowband THz emission
4. Conclusion

Outline

SASE Free Electron Laser

Self Amplified Spontaneous Emission (SASE)

- amplification, up to saturation, of the spontaneous emission produced by the ebeam entering in the undulator
- requires high quality ebeam with very high peak current ($\sim$ kA)
- typical bunch length in the $1 - 100$ fs
- usually poor longitudinal coherence (temporally and spectrally spiky emissions)



Incoherent emission: electrons randomly phased

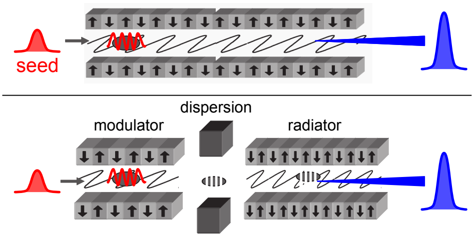
Coherent emission: electrons bunched at radiation wavelength

[B.W.J. McNeil & N.R. Thompson, Nat. Photon. 239 (2010)]

Elettra Sincrotrone Trieste

Seeded FEL

Use of external *seed* laser
$\rightarrow$ control the distribution of the electrons within the bunch



Benefits of a seeded FEL:

- final FEL pulses inherit properties of the seed
- improvement of **temporal coherence** of FEL pulses
- control of time duration and bandwidth
- low arrival time jitter
- reduction of undulator chain to reach saturation

Drawback:

- no seeding sources at very short wavelength range
- spectral properties sensitive to the ebeam longitudinal phase-space

Microbunching instability in LINACs

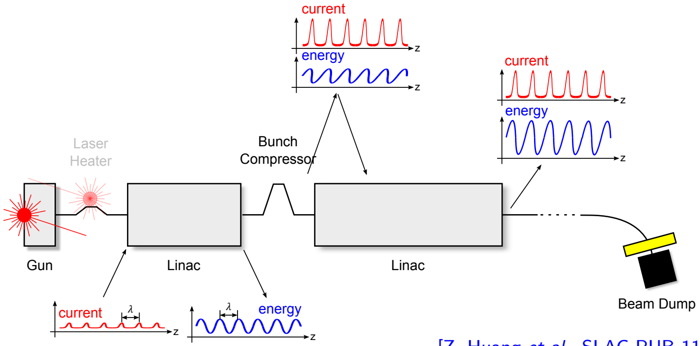
- Gain mechanism:

density modulation $\xrightarrow[\text{linac}]{}$ energy mod. $\xrightarrow[\text{bunch comp.}]{}$ density mod.

- Main ingredients:

LSC (Longitudinal Space Charge) & CSR (Coherent Synchrotron Radiation)

[Saldin *et al.*, NIMA **490**, 1 – 8 (2002)], [Saldin *et al.*, NIMA **528**, 355 – 359 (2004)]

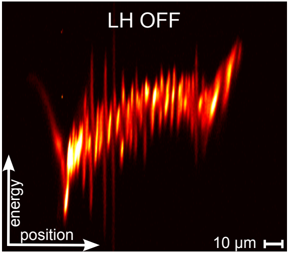


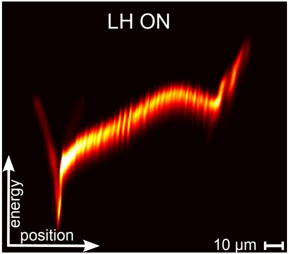
[Z. Huang *et al.*, SLAC-PUB-11597 (2005)]

High-quality e-beam for high-gain FELs ?

- Broadband μBI with maximum gain around **few μm**.
- Longitudinal phase-space modulated in energy and/or density through μBI.
- Increase of $\langle$energy spread$\rangle$ comparable to the FEL parameter
  $\rightarrow$ suppression of SASE gain.

- One of the methods to control and suppress the μBI: the **laser heater (LH)**
  $\rightarrow$ induces a controllable increase of the $\langle$energy spread$\rangle$ to damp the μBI.
  [Saldin *et al.*, NIMA **528**, 355 – 359 (2004)]





[Ratner *et al.*, PRSTAB **18**, 030704 (2015)]

Microbunching and seeded FELs

- A seeded FEL is more sensitive to e-beam phase-space properties.
- Small imperfections on the phase-space have strong impact on FEL spectrum.

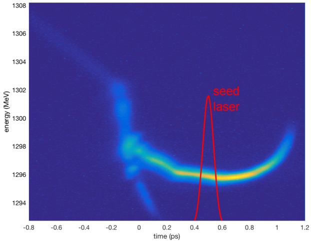
$$\downarrow$$

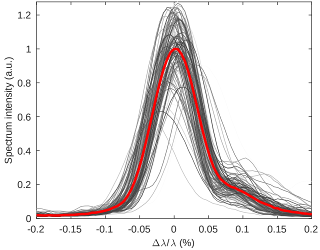
- seed laser modulation (k_{S}) superposed to μBI modulation ($k_{\mu\mathsf{B}}$)
- generation of FEL pulses via frequency mixing process:

$$k_{\mathsf{FEL}} = h \times k_{\mathsf{S}} \pm m \times k_{\mu\mathsf{B}}$$

- stochastic effect on the FEL spectrum

  [Z. Zhang *et al.*, PRAB **19**, 050701 (2016)]





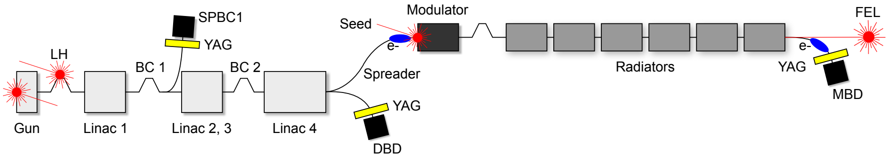
Outline

"Seeded Linac"

- Principle

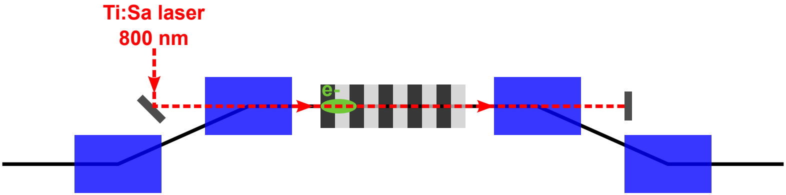
Take advantage of the **microbunching instability gain** occurring in the linear accelerator to imprint a **coherent modulation** onto the electron beam, using a dedicated **laser heater pulse shaping** [E. Roussel *et al.*, PRL **115**, 214801 (2015)]

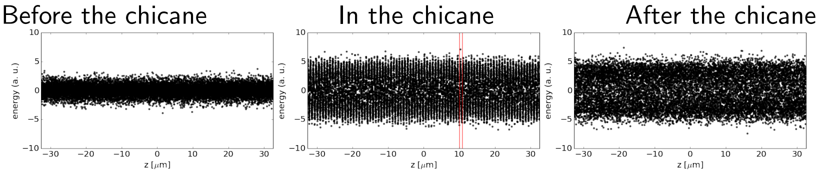
→ seeded microbunching instability !



What's the laser heater (LH)?

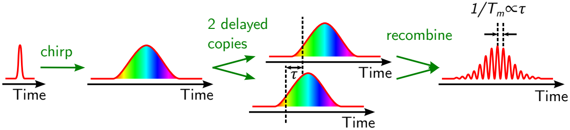
The LH induces a homogenous increase of the uncorrelated energy spread to damp the μBI. Optical wavelength washed out at the exit of the chicane.





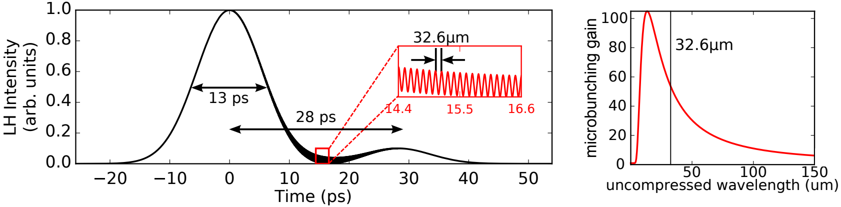
LH pulse shaping

- Generation of a modulated laser pulse using chirped pulse beating technique



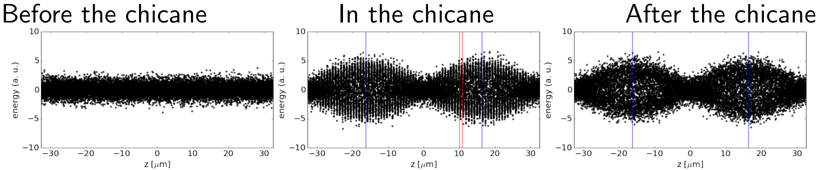
[Weling and Auston, JOSA B **13**, 2783 (1996)]

- LH intensity profile with beating frequency inside the gain curve of μBI

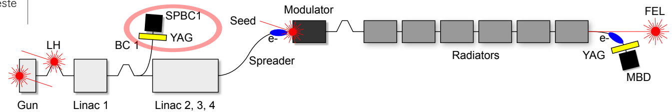


Modulation of the electron beam (1)

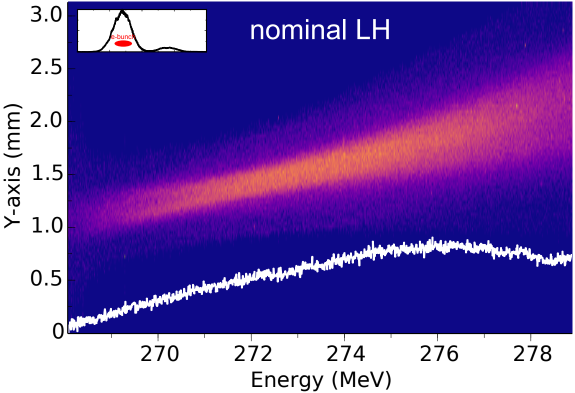
- Can we really modulate the ebeam using LH beating ?
  Smearing condition of the LH chicane: $\lambda \ll 2\pi |R_{52}\sigma_{x'}| = 4\ \mu$m.
  Here, optical wavelength = 780 nm and beating wavelength = 32.6 μm.



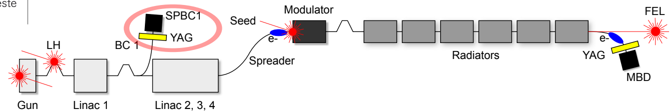
Modulation of the electron beam (2)



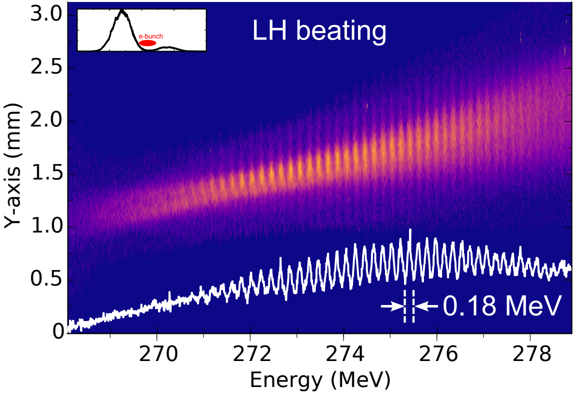
- Exp. observation of energy distribution (in SPBC1)



Modulation of the electron beam (2)

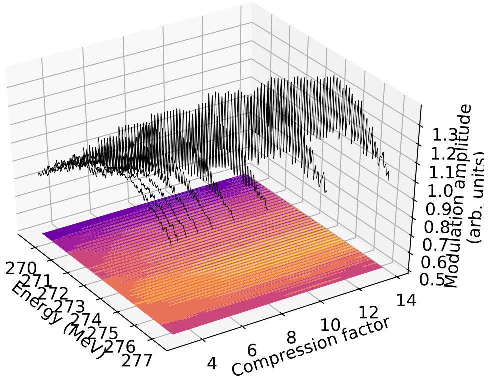


- Exp. observation of energy distribution (in SPBC1)

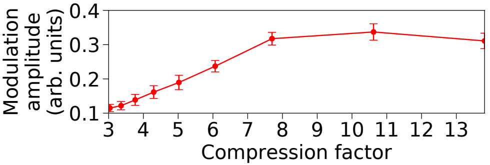


Linear energy chirp (spectro-temporal mapping) $\rightarrow$ 0.18 MeV $\equiv$ 32.4 μm

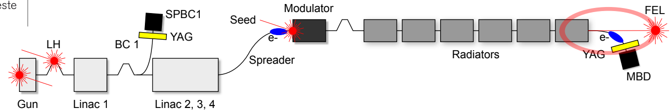
Microbunching amplification



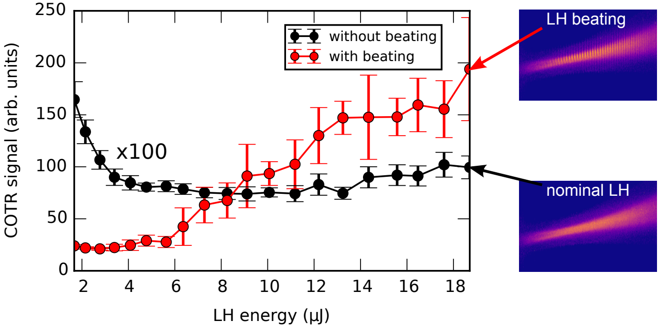
Initial **energy spread modulation** amplified by μBI gain and converted into **energy and density modulation** at the bunch compressor.



Microbunched electron beam in the undulators



- Transport of the microbunched ebeam in the undulator chain

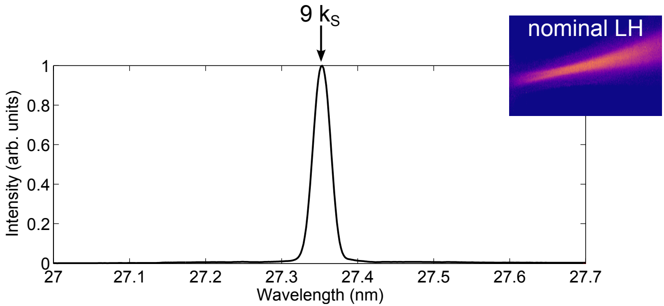


Observation of strong coherent transition radiation (COTR) in the IR domain at the exit of the undulators in case of microbunched ebeam.

Impact on FEL emission

FERMI is a seeded FEL based on high-gain harmonic generation (HGHG).

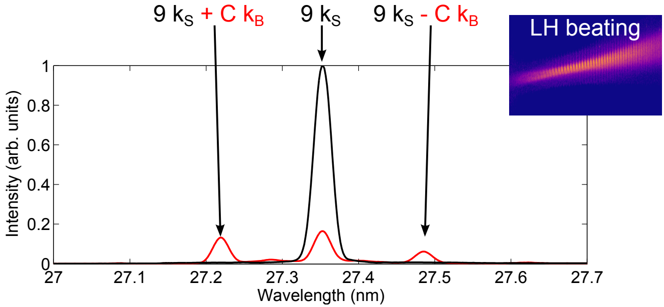
$$k_{\mathsf{FEL}} = h k_{\mathsf{S}}$$



Impact on FEL emission

FERMI is a seeded FEL based on high-gain harmonic generation (HGHG).

$$k_{\mathsf{FEL}} = hk_{\mathsf{S}} \pm mCk_{\mathsf{B}}$$

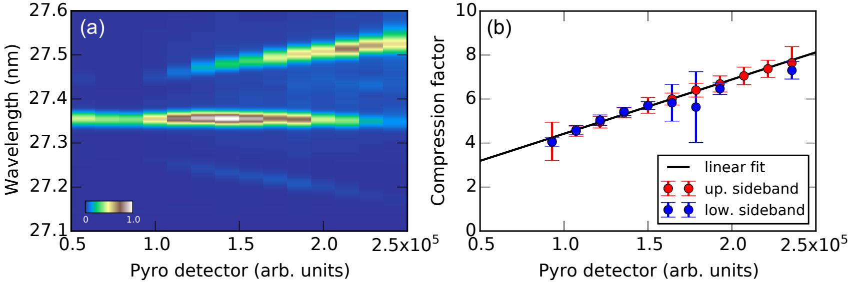


Observation of **sidebands** coming from a **frequency mixing** between the seed wavelength and the beating wavelength (scaled by the compression factor C).

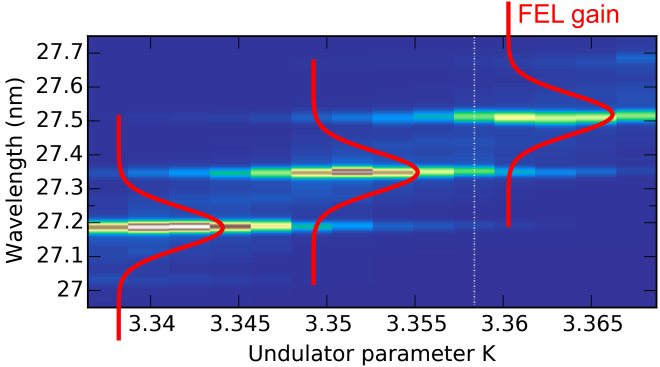
Tunability of FEL spectrum

Tuning of the sideband position by acting:

- on the **compression factor** C or on the beating wavelength k_B.



FEL sideband selection

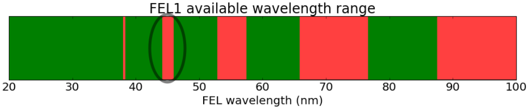


Selection and FEL amplification of one sideband by tuning the radiator resonance condition.

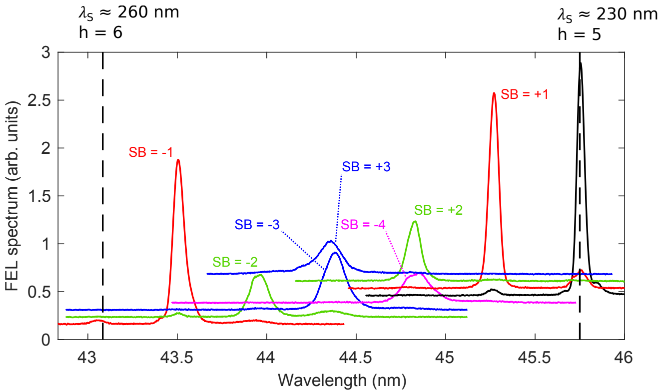
FEL in the "dark" part of the seed laser

Elettra Sincrotrone Trieste

- FEL-1 range for the "nominal" FERMI seed laser operation (230 – 260 nm)

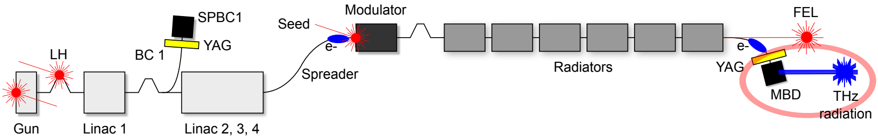


- Increased tunability via LH beating-induced sidebands



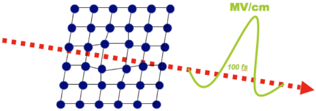
Outline

Towards tunable narrowband THz emission



- TeraFERMI: parasitic THz beamline in the beam dump area. Ultra-short, high-power THz pulses between 0.3 – 15 THz to pump on electronic, vibrational and magnetic excitations.
  [A. Perucchi *et al.*, Rev. Sci. Instrum. **84**, 022702 (2013)]

Wavelength range THz pulse energy Operation conditions	1 mm – 20 μm 50 μJ – few mJ FEL-1/FEL-2 10/50 Hz

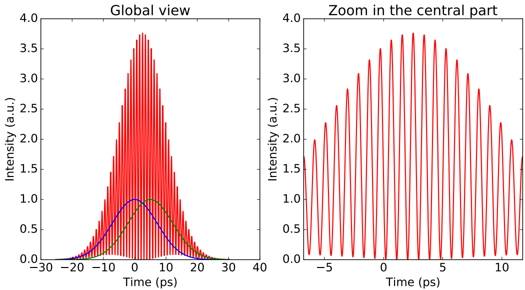


Courtesy of A. Perucchi

LH pulse shaping

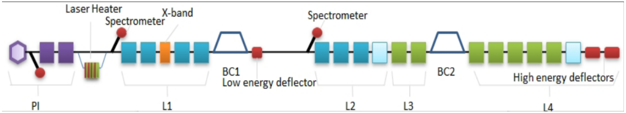
Strategy: modulate the electron beam in the sub-THz/THz range and take advantage of the bunch compression to reach the THz/tens of THz range.

- First application in storage rings (UVSOR, Japan): [C. Evain et al., Phys. Rev. ST Accel. Beams 13, 090703 (2010)]
- Calculation for LINAC: [Z. Zhang et al., Phys. Rev. Accel. Beams 20, 050701 (2017)]



1 THz $\equiv$ 300 μm $\rightarrow$ no μBI gain in these wavelengths ...
but no need because strong modulations are available at the LH !

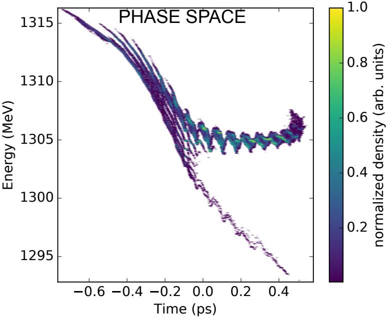
Simulation of ebeam dynamics

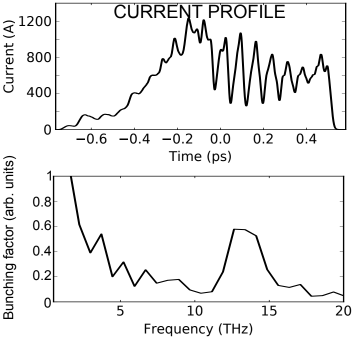


Comp. factor $C_1 \approx 4.1$ $C_2 \approx 1.8$

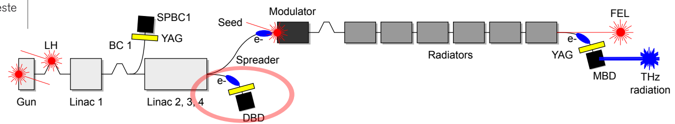
$R_{56,1} = -42$ mm $R_{56,2} = -20$ mm

Simulation with ELEGANT. Initial condition: $\lambda_B = 200\mu$m, $\Delta E = 50$ keV.

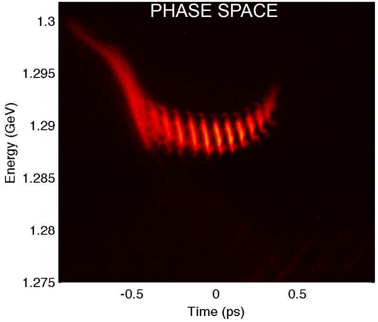


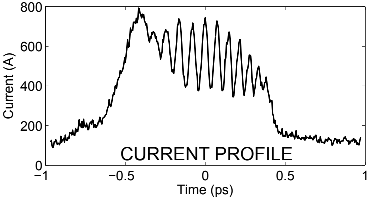


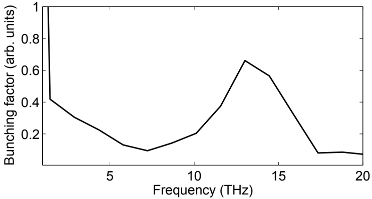
Experimental THz-modulated ebeam



- Observation of a modulated beam in the tens of THz range at the end of the linac starting from an initial modulation in LH around 2 THz.

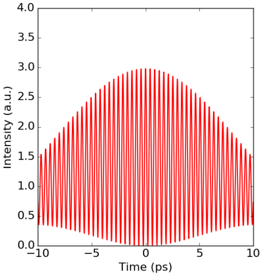




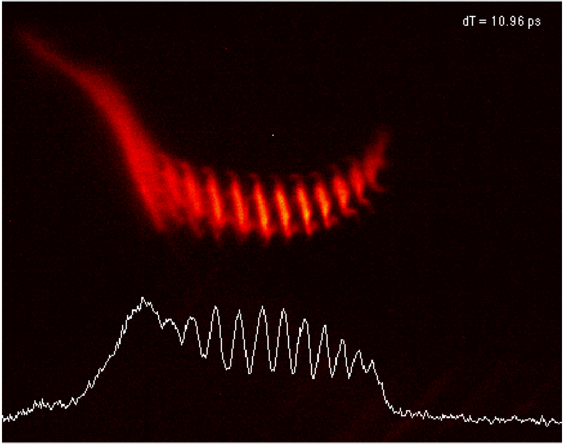


Tunable THz modulation

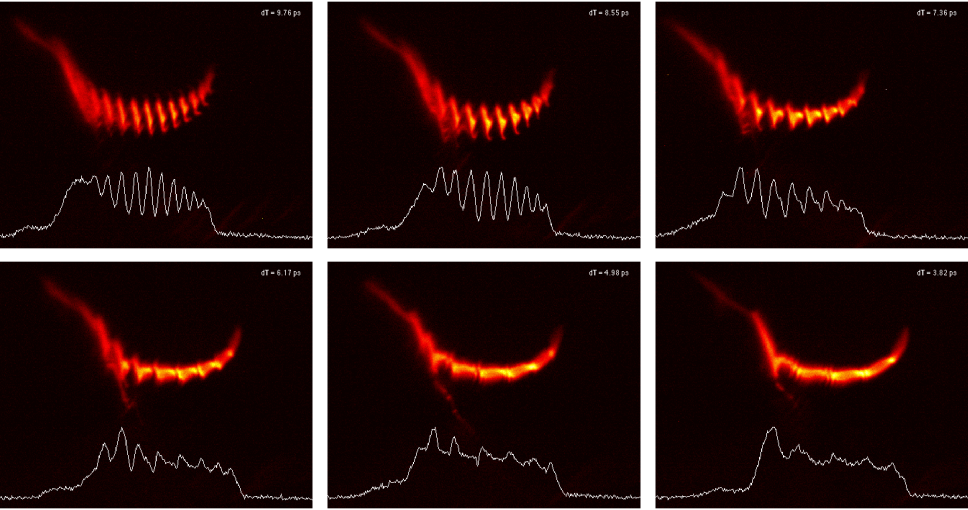
LH PROFILE



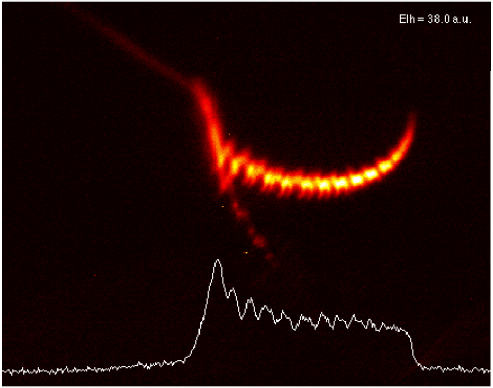
PHASE-SPACE

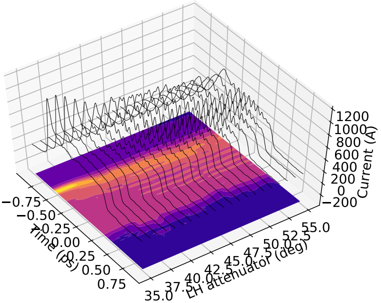


Tunable THz modulation (bis)



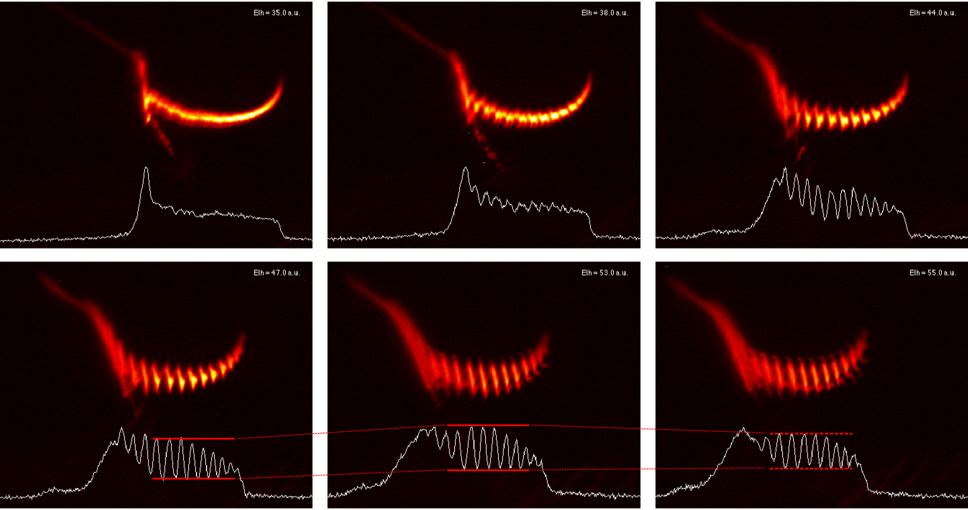
Optimization of modulation amplitude





Optimization of the rotation of the structures by controlling the initial modulation amplitude at the LH or by acting on the dispersion strength.

Optimization of modulation amplitude (bis)



Outline

Conclusion

- LH pulse shaping: an alternative method to probe and investigate the microbunching instability.

- LH: a powerful tool to control the FEL spectro-temporal properties.
  - Generation of tunable, incommensurate, multicolor FEL pulses.
    [E. Roussel *et al.*, PRL **115**, 214801 (2015)]
  - Non-gaussian ebeam heating for higher harmonic frequency conversion.
    [E. Ferrari *et al.*, PRL **112**, 114802 (2014)]
  - LH pulse shaping for FEL pulse duration control.
    [V. Grattoni, IPAC17, WEPAB034]

- Towards the generation of intense tunable narrowband THz radiation.

- And what about SASE FELs... ?

Acknowledgment

Many thanks to the FERMI machine physics group and to all the FERMI team.

Eugenio Ferrari, Enrico Allaria, Giuseppe Penco, Simone Di Mitri, Marco Veronese, Miltcho Danailov, David Gauthier and Luca Giannessi.

⇒ http://www.elettra.eu/about/careers/ref-a-17-01-accelerator-physicist-at-fermi.html ⇐